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TOLERANCE OF THE NECK TO INDIRECT IMPACT

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The literature has been reviewed to determine available neck tolerance criteria for indirect impact. Seven sources of information were found, along with four papers containing supporting information. Four of the seven papers contain neck load data for inertia loading of the heads of volunteers (up to AIS 1 rating), embalmed cadavers and Hybrid III dummy, during auto crash simulation tests. One reference contains crown impact peak force limits for cervical spinous process fracture (AIS 3). Two references, both related to the same study, published peak neck loads and axial force-time tolerance curves for crown impact to

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the Hybrid III dummy, based upon simulation of catastrophic fracture-dislocation football neck injury environment. Despite the differences in the subjects and environments, there is a general coherence among the data showing increasing loads with increasing levels of injury severity.

TOLERANCE OF THE NECK TO IMPACT ACCELERATION

by

Voigt R. Hodgson, Ph.D.

ABSTRACT

The literature has been reviewed to determine available neck tolerance criteria for indirect impact. Seven sources of information were found, along with four papers containing supporting information. Four of the seven papers contain neck load data for inertia loading of the heads of volunteers (up to AIS 1 rating), embalmed cadavers and Hybrid III dummy, during auto crash simulation tests. One reference contains crown impact peak force limits for cervical spinous process fracture (AIS 3). Two references, both related to the same study, published peak neck loads and axial force-time tolerance curves for crown impact to the Hybrid III dummy, based upon simulation of catastrophic fracture-dislocation football neck injury environment. Despite the differences in the subjects and environments, there is a general coherence among the data showing increasing loads with increasing levels of injury severity.

1.0 Introduction

Until very recently, tolerance data for indirect loading of the neck was virtually non-existent. A paper by Melvin (1) to be presented at the 1979 SAE Congress concurs with this statement. A new SAE Information Report J885b (2) has been prepared for publication. It describes current (as of December 1976) knowledge in human loading behavior under impact conditions typical of automobile collisions. It is intended as a review of quantitative tolerance data but no specific limits are recommended. The neck data cited (3-5) apply to adult males and are limited to: volunteer studies of static strength tests for reactions at the occipital

condyles to loads applied directly to the head, and; dynamic neck reactions calculated at the occipital condyles for volunteers and cadavers strapped to a chair on an accelerator sled.

Only in the dynamic tests was the injury threshold reached. One of the volunteers achieved an AIS 1 rating (pain but no injury), and ligamentous damage (AIS 3) was produced in one cadaver.[1] Their results indicated that the neck appears to be at least three times stronger in resisting flexion than extension. Not included in the above Report was the work of Gadd, et al, (6) who determined the angular limits short of significant injury in unembalmed subjects loaded statically and dynamically through the head similar to tests in References 3-5.

Since the December 1976 cutoff date for the J885b report three additional papers relating to neck injury tolerance to indirect loads have been published. Two studies of injury environments have been made with the Hybrid III dummy (9) and the third delivered impulses to the crowns of fresh intact human cadavers (10). In chronological order, the experimental investigations into the tolerance of the neck to indirect loading are described below.

2.0 Description of Experiments

2.1 Inertial Loading of the Heads of Volunteers (3, 4)

The subjects were restrained in a rigid chair which was mounted on an impact sled. The sled traveled on two horizontal rails and was accelerated

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[1] Abbreviated Injury Scale (AIS) for injury severity (7):

Code	Category
0	no injury
1	minor
2	moderate
3	severe (not life threatening)
4	serious (life threating, survival probable)
5	critical (survival uncertain)
6	maximum (currently untreatable)
9	unknown

pneumatically over a distance of 1.8 m (6 ft) to a prescribed velocity. During the acceleration stroke, a headrest was used to maintain the head in an upright position. After reaching its prescribed velocity, the sled coasted for a short distance before being stopped by an approximately square deceleration pulse.

The restraint system consisted of lap belt and two individual shoulder harnesses which criss-crossed the chest at midsternum. Each belt was made of nominally 5 cm (2 in) wide, standard automotive webbing material fastened with a standard automotive seat belt buckle. The upper shoulder harness mounts were adjustable so that this portion of the harness could be kept horizontal, independent of the size of the subject. In addition, to these restraints the subject's feet were securely fastened to the foot support and his wrists were strapped to the arm rest to prevent flailing of these appendages during the run. Two pairs of accelerometers were mounted in the mouth and on a light weight fiberglass helmet which was securely fastened to the subject's head.

The object of the research project discussed in Reference 3 was to determine the kinetic, kinematic, and physiological effects produced by varying the mass, center of gravity and mass motion of inertia of the head by the addition of a helmet. Consequently, tests were conducted only in forward flexion with lead weights attached to the fiberglass helmet in various configurations. In a later work (4) four volunteers were subjected to similar test conditions but with the addition of rearward extension, lateral and oblique flexion and without helmets or lead weights.

2.2 Direct Impact to the Crown of the Hybrid III Dummy (8, 9)

The purpose of these tests was to simulate several accidents which were alleged to have happened in football blocking and tackling drills when the players were struck on the crown of the helmet by a dynamic blocking machine. The dummy was strapped in a stationary supine position to a sled which was free to move on a conveyor after being struck by the

moving tackling block which had been involved in a field accident. The 25 hg (55 lb) padded bag was propelled at velocities of 2, 4.1, 5.2 and 7 m/s (10, 14, 17, and 23 ft/s) into impact with the crown of several types of football helmets worn on the head of the dummy. The majority of the impacts delivered almost purely axial loads but a few were delivered with the shoulder raised (flexion) and buttocks raised (extension). The dummy was instrumented with a triaxial accelerometer mounted at the center of gravity of the head, a load cell at the atlanto-occipital junction to record axial force, shear force and bending moment, and a uniaxial accelerometer mounted in the thorax aligned along a superior-inferior axis.

2.3 Inertial Loading of the Head of the Hybrid III Dummy (10)

The dummy was "calibrated" relative to a field accident injury data base from Sweden for three-point lap-shoulder belt occupants involved in frontal crashes. The field accident data base used in this study is fully described in the publications of Patrick, et al., (11). It consists of 128 cases of Volvo accidents in Sweden, ninety-eight of which satisfied the criteria of the study and thirty-two of which were rated on the AIS Injury Scale of at least one. Sixty-six of the ninety-eight cases had no injury. The barrier equivalent velocity (BEV) ranged from 3-64 m/s (2-40 mph). There were twenty-nine females and sixty-nine males in the group ranging in age from 18-84 years. In the field accident study group were five AIS 1 neck injuries.

The Wayne State University WHAM III sled facility was utilized to simulate the field accidents. This device towed a modified 1970 Volvo sedan with a Hybrid III dummy restrained in the right front passenger seat by a standard three-point single loop belt system. A pneumatic propulsion mechanism accelerated the car and sled to the desired speed, after which the combination is stopped by a programmable hydraulic snubber set for a slightly skewed half sine pulse, the duration of which ranged from 112 to 135 ms. The dummy was extensively instrumented for these tests but with

respect to the head it had a triaxial accelerometer (AP, SI, and Lateral sensors), and at the head-neck interface the loads monitored were axial force (SI), shear force (AP) and bending moment (flexion-extension). Three tests were run at 32.2 km/h (20 mph) BEV and three tests at 43.4 km/h (30 mph) BEV. There were no direct impacts to the head in any of these tests.

2.4 Direct Impact to the Crown of Fresh Cadavers (12)

Six males and five female fresh cadavers were used in this study. The subjects were placed in a supine position and the cervical spine was aligned along the impactor axis. Using axial alignment the investigators were attempting to achieve the maximum load carrying capability of the spine, thereby improving chances for basal skull fracture. The machine which was used to deliver the impacts consisted of an air cylinder and a ground and honed cylinder and transferred its momentum to the impact piston. Instrumentation for this series consisted of a piston accelerometer which yields an inertially compensated piston force as a function of time. Resultant, horizontal and vertical displacement and their first and second derivatives were obtained by analysis of high-speed movies taken at 3000 frames/s.

3.0 Results

3.1 Inertial Loading of the Heads of Volunteers

The results obtained from References 3 and 4 for forward flexion, rear extension and various degrees of lateral flexion are given in Table 1. No injuries were produced, but pain was experienced by one volunteer and an AIS rating of one was assigned. Similar tests were carried to higher levels in cadavers, with results given in Table 1 for forward flexion and rearward extension. Damage was experienced in only one case which was assigned AIS rating of 3, designating ligamentous damage. In Table 1 the neck torque given for forward flexion included the moment of the chin force taken with respect to the occipital condyles. The authors found that the resultant torque was an excellent indicator of neck strength. Based on their

cadaver data, they suggested tolerance levels for 50th percentile adult male. For flexion a resultant torque of 190 N · m (140 ft-lb) was proposed as a lower bound for an injury tolerance limit. This torque level did not produce any discernable ligamentous damage to a human cadaver. Comparing the Table 1 torque data, the neck appears to be at least three times stronger in resisting flexion than extension. It was noted that this is consistent with the anatomical fact that there are more muscles located posterior to the cervical spine, and these muscles should generate forces in resisting flexion than those produced by the limited number of anterior muscles in resisting extension. In addition, there is a sizable increase in the effective moment arm of the posterior muscles and ligaments when the chin contacts the chest.

3.2 Direct Impact to the Crown of the Hybrid III Dummy (8, 9)

Shown in Table 1 are the peak neck loads measured at the atlanto-occipital junction and the SI head accelerations measured at the head CG of the Hybrid III dummy under field accident paralyzing neck injury crown impact conditions. Since most biological tissues have time dependent properties which result in an increase in their load carrying capacity as the duration of loading decreases, the authors published two injury reference curves for axial compression neck loading. One curve is applicable to the general adult population and the other tolerance curve which is higher, applies to high school football players. Both references apply to measurements made on the Hybrid III dummy. Explanations and restrictions on the use of the curve are given in Reference 9.

3.3 Direct Impact to the Crown of Fresh Cadavers (12)

The primary skeletal injuries in this series of tests were spinous process fractures. The type of fracture and high speed movie analysis indicated a compressive arching of the cervical spine. HSRI investigators found that the arching followed the normal lordotic curvature of the cervical spine and appeared to depend on the initial rotation of the head

and axial alignment of the spine. They found that if the head is rotated rearward or the head placed above the axis of the spine, the arching is increased. No dislocations, no anterior compressive fracture of the bodies of the vertebrae, nor any basal skull fractures were found. This was a pilot study and its utility is limited, but the data indicated that peak impact force of 5.7 kN (1280 lb) is a level above which cervical spine fracture will begin to occur for an average cadaver under conditions of their experiment.

CONCLUSIONS

1. There is a small but significant body of data for tolerable and injurious neck loading that is beginning to accumulate.
2. Most of the available tolerance data for indirect loading of the neck has been obtained from inertia loadings of the heads of volunteers and cadavers.
3. Inertia loading of the head in car crash field accident studies has provided some measured and calculated data, and impact environment conditions up to the level of pain - no injury (AIS 1) for forward flexion in the volunteer; up to ligamentous damage in embalmed cadavers for rear extension, and; measured neck loads for AIS 1 in forward flexion of the Hybrid III dummy.
4. Neck loads for direct impact to the crown of the helmeted head of the Hybrid III dummy in an assumed catastrophic cervical fracture-dislocation environment (AIS 5) have been measured and tolerance curves for axial compressive neck loads measured in this dummy have been published.
5. Peak forces have been measured during impact with a piston on the crowns of head of fresh cadavers during which several spinous process fractures occurred.

6. For inertia loading pain - no injury (AIS 1) in the volunteer produced shear forces (797 N) calculated to be roughly one-half as high as those in the cadaver (no damage observed), which were in turn roughly one half as high as those measured in the Hybrid III dummy (AIS 1 simulation) for forward flexion.

7. For direct loading, peak axial loads in the fresh cadaver to produce spinous process fracture (AIS 3) were lower than those measured in the Hybrid III dummy under catastrophic fracture dislocation (AIS 5) injury environment.

8. There is intense activity in the study of mechanisms of neck injury to indirect impact and should be monitored closely for input to the head and neck protection problem.

TABLE 1

COMPARISON OF PEAK NECK LOAD DATA FOR INERTIA AND DIRECT IMPACT LOADING OF THE HEADS OF VOLUNTEERS, CADAVERS, AND THE HYBRID III DUMMY

LOADING CONFIGURATION	Torque (N·m)	ft-lb	Shear (N)	Force lb	Axial (N)	Force lb	AIS Rating	COMMENTS
Inertia Loading - Volunteers (2, 3):								
Forward Flexion 0°	88.2	(65.0)	787	(177)	--	--	1	Pain no injury
Rearward Extension 180°	30.5	(22.5)	231	(52)	249	(56T)∿	0	No injury
Lateral Flexion 90°	45.2	(33.5)	792	(178)	--	--	0	No injury
Lateral Flexion 135°	18.0	(13.3)	311	(311)	356	(80T)	0	No injury
Lateral Flexion 45°	31.2	(23.0)	440	(440)	165	(37T)	0	No injury
Inertia Loading - Cadavers (2, 4):								
Forward Flexion 0°	190	(140)	1588	(357)	--	--	0	No damage
	176	(130)	1944	(437)	--	--	0	No damage
Rearward Extension 180°	47	(35)	--	--	--	--	0	No damage
	57	(42)	--	--	--	--	3	Ligamentous damage
Inertia Loading - Hybrid III Dummy (9):								
Forward Flexion 0°	76	(56)	1180	(265)	850	(190T)	*	mean of 3 replications v=32.2 kM/h (20 mph) BEV
	152	(112)	2970	(670)	3290	(740T)	*	mean of 3 replications v=48.3 kM/h (30 mph) BEV
Direct Loading - Fresh Cadavers (11):					Impact Force† lb	(N)		
Crown Impact					3600	(809C)	3	long thin necks, little musculature Cervical spine fracture
					5700	(1280C)	3	Cervical spine fracture
Direct Loading - Hybrid III Dummy (7, 8):								
Crown Impact	30$^{\tau}$	(22)	1330	(300)	4000	(900C)	5	Catastrophic cervical fracture/dislocation- adults
	39	(28)	2220	(500)	6670	(1500C)	5	Catastrophic cervical fracture/dislocation- High School football players

*There was a total of 5 AIS 1 neck injuries in the (98) field accident cases being simulated by the dummy. Two occurred at a lower BEV and three at the 48.3 kM/h (30 mph) appears to be a 14 percent probability of an AIS 1 maximum neck injury when the 48.3 kM/h (30 mph) BEV data levels are reached.

†The neck axial loads would be lower by the amount of the head SI inertia force which is not available.

τTorque deliberately minimized to achieve near-axial loading.

∿T-Tension; C-Compression

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